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Thermal Performance Assessment of Envelope Retrofit Strategies for Office Spaces in Composite Climates#

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ABSTRACT

Building envelope retrofit strategies enable reducing cooling loads in warm climates and optimising energy use. However, these strategies may be tailored to specific building types and their effectiveness depends on the climatic conditions they operate under. This paper presents an open-source model to assess the effects of envelope retrofits under the climatic conditions of India. Using OpenModelica, an office building located at Delhi was modelled using real construction and occupancy data. The indoor heat gain through the building envelope was quantified for different retrofitting scenarios. Results show thermal insulation is more effective than phase change material in mitigating heat gain and can reduce the heat gain by up to 400 W in summer. The findings offer insights for sustainable cooling, whereas the developed model offers an open-source tool to quantify cooling demand in office buildings.

Keywords: Building envelope, phase change material, thermal insulation, indoor heat gain

NOMENCLATURE

Abbreviations	
DSC	Differential scanning calorimeter
HVAC	Heat, ventilation and air conditioning
ICAP	India Cooling Action Plan
PCM	Phase change material
PUF	Polyurethane foam
Symbols	
A	Area [m^2]
Q	Heat flow [W]
I	Solar radiation [W/m^2]
T	Temperature [K]
c_p	Specific heat capacity [J/(kg·K)]
h	Convective heat transfer coefficient [W/(m^2·K)]
k	Thermal conductivity [W/(m·K)]
t	Time [s]
α	Solar absorptivity
ϵ	Solar emissivity
ρ	Density [kg/m^3]
ΔR	Long-wavelength radiation exchange between the envelope surface and the ambient [W/m^2]

1. INTRODUCTION

Urbanisation and rising global temperatures have led to an increase in cooling demand in buildings and, subsequently, global energy consumption. The energy required for cooling buildings is almost one-third of the total electricity demand and this is forecasted to increase three times by 2050 [1]. The electricity demand by air conditioning systems alone is expected to rise to 1,200 TWh by 2035 [1,2].

The need for cooling is particularly acute in countries located in the tropical belt such as India. The India Cooling Action Plan (ICAP) forecasts an almost eight-fold increase in cooling demand by 2038 relative to 2018, with space cooling in buildings alone projected to grow nearly eleven-fold. Meanwhile, rising temperatures are already placing immense strain on India's electricity grid: every 1 °C increase in ambient temperature is driving an additional 7 GW in peak electricity demand, nearly double the value from five years ago [3].

Previous research has shown that retrofitting strategies such as thermal insulation, phase change materials (PCMs) and passive design elements can significantly reduce cooling loads and enhance energy efficiency in buildings. PCMs, due to their high latent heat storage capacity, provide almost isothermic conditions near their melting point [4]. Thereby, PCMs are actively used in construction materials, walls, roofs and façades for thermal management of indoor conditions [5–8]. On the other hand, the low thermal conductivity of insulation materials embedded in building envelopes leads to an effective reduction in indoor heat gain under warm climatic conditions [9].

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The effectiveness of envelope retrofits is largely dependent upon outdoor ambient conditions. Seasonal and diurnal swings in ambient temperature and solar radiation dictate how effectively retrofits can curtail indoor heat gain from warm outdoors. It is unclear whether PCM is an overall more suitable option than thermal insulation, which calls for further investigation.

A methodology to quantify the cooling demand of dwellings under UK ambient conditions was reported in [10]. However, availability of open-source tools as in [11] to quantitatively assess and compare the effects of envelope retrofits under tropical composite climatic conditions is not available. Since buildings in India are constructed differently from those in European regions and the climate of India significantly differs from that of traditionally colder countries like the UK, further insight into the tropical Indian context is required.

This paper presents an open-source model to assess retrofit interventions on the thermal performance of Indian buildings. Leveraging empirical data from an office building at the Indian Institute of Technology Delhi, and conducting dynamic simulations with OpenModelica, indoor heat gain reductions using thermal retrofits are evaluated. The utility of the developed model is demonstrated with a parametric analysis to assess the performance of retrofits with different dimensions and across seasons. The findings offer actionable insights for sustainable cooling strategies which align with India's national objectives under the Kigali Amendment and ICAP, guiding both infrastructure-level retrofits and evidence-based policy measures.

2. MATERIAL AND METHODOLOGY

2.1 Reference office space

The office space studied in this paper is located in Delhi, India (28.7° N, 77.1° E), which exhibits composite climatic conditions. A high-level schematic is provided in Fig. 1. The room dimensions are 6 m in length, 4.6 m in width and 3.5 m in height. A glazed window, with a height of 2 m and a width of 4 m, is positioned on the northern façade to allow diffuse daylight penetration while minimising direct solar heat gain.

The building envelope consists of three layers: lightweight plaster on the interior surface, burnt brick in the middle and lightweight plaster on the exterior. The thermal properties of the wall, roof and glazing materials are provided in Table 1. The office was assumed to operate at full occupancy during weekdays, corresponding to 0.3 persons per square meter of floor area, from 9:00 a.m. to 5:00 p.m. Occupancy was halved from noon for one hour to accommodate a lunch hour. No occupancy was considered during weekends.

In addition to occupants, heat gains from office equipment were considered. The indoor equipment comprises four computers and two workstations, with their respective energy consumption monitored through a smart plug. This resulted in internal heat gains of 1,100 W per hour during office hours and 553 W during the lunch break. The indoor temperature was assumed to be maintained at 24°C throughout the week, irrespective of occupancy, to ensure the integrity of scientific equipment and chemical reagents stored in the office.

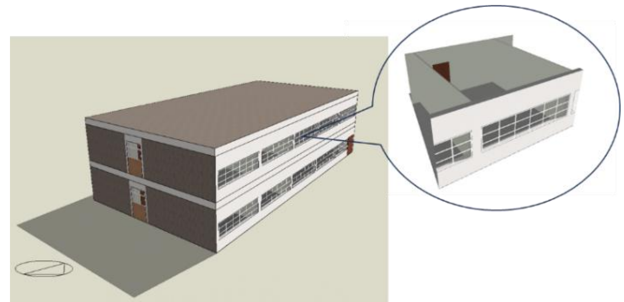


Fig. 1: Office space in Delhi

Table 1. Properties of materials [12,13]

Material	Dimension [mm]	ρ [kg/m^3]	k [W/(m·K)]	c_p [J/(kg·K)]
Lightweight plaster	12.5	600	0.16	1,000
Brick	225	1,920	0.72	840
PCM (octadecane)	5-15	777	0.14	2,180
Insulation (PUF)	5-15	30	0.086	1,800

2.2 Retrofitting materials

The materials comprising the building envelope are locally available and intensively used for construction in India. The PCM considered is octadecane, with a latent heat capacity of 290.35 kJ/kg and a melting temperature of 27.97 °C, which is in proximity to the thermal comfort range in India. These properties were further confirmed experimentally using a differential scanning calorimeter (DSC). The insulation considered was polyurethane foam (PUF) due to its high insulating capacity and low cost.

Fig. 2 shows the variation of normalised heat flow of the PCM with respect to temperature as obtained with the DSC. Negligible heat absorption was recorded until 26.23 °C, at which melting began, which persisted until full phase transition was reached at 27.97 °C. The enthalpy of fusion was calculated as 290.35 kJ/kg. The PCM characterisation was done three times to ensure reliability in these results, yielding a variation of 1.1% in latent heat and 0.15 °C in phase change temperature.

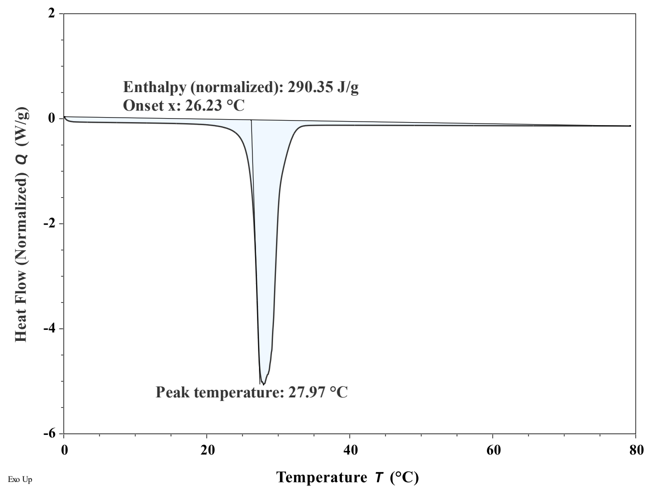


Fig. 2: Thermogram of octadecane (PCM)

The initial thickness of the PCM and insulation was considered as 10 mm, which is consistent with previous studies reported in the literature [9,12].

2.3 Mathematical Modelling

The transient heat conduction of a material is given by

$$k\frac{\mathrm{d}^2T}{\mathrm{d}x^2} = \rho c_p \frac{\mathrm{d}T}{\mathrm{d}t} \tag{1}$$

where k is the thermal conductivity, ρ is the density, c_p is the specific heat, x is the thickness and T is temperature. The one-dimensional transient heat conduction through multilayered building components was modelled using the "Multilayer" block available in the Modelica Buildings Library. Each wall and roof layer was assigned dimensions and thermophysical properties as outlined in Table 1. Modelica solves the heat diffusion equation to compute the transient heat transfer using k, ρ, c_p, x and T as governing inputs.

Convective heat transfer between envelope surfaces and surrounding air was calculated by standard heat balance equations:

$$Q_{c,in} = h_i A(T_{int} - T_{in}) \tag{2}$$

$$Q_{c,ext} = h_o A(T_{sol} - T_{ext}) \tag{3}$$

where $Q_{c,in}$ is the convective heat transfer between the internal envelope surface and the indoor air, $Q_{c,ext}$ is the convective heat transfer between the external envelope surface and the outdoor air, h_i and h_o are the internal and external convection coefficients, A is the surface area of the envelope, T_{sol} is the sol-air temperature, T_{int} and T_{ext} are the temperatures of internal and external envelope surfaces, and T_{in} is the indoor air temperature. Coefficients for indoor and outdoor convection were adopted as 23.14 W/(m^2·K) and 5 W/(m^2·K) [11].

The sol-air temperature was included to account for solar radiation and outdoor temperature as a combined thermal boundary condition on the envelope using

$$T_{sol} = T_o + \frac{\alpha I}{h_o} \qquad \text{(for wall)} \tag{4}$$

$$T_{sol} = T_o + \frac{\alpha I}{h_o} - \frac{\varepsilon \Delta R}{h_o} \qquad \text{(for roof)} \tag{5}$$

where T_o is the outdoor air temperature, I is the incident solar radiation, α and ε are the solar absorptivity and long wavelength emissivity of the envelope's outer surface, and ΔR is the long wavelength radiation exchange between the envelope surface and ambient, with a value of 63 W/m^2 [11].

IES VE was used to simulate solar radiation due to its proven reliability, as the software has been validated against standards such as ASHRAE 140, CIBSE TM33, and ISO 52000 [11]. The Hay model, integrated within IES VE, was applied to compute incident solar radiation. The software provides a graphical interface to generate three-dimensional models of houses with customised shapes and geographic coordinates. Based on geometry, orientation and location, the Hay model estimates hourly radiation on walls and roofs [14].

Fig. 3 illustrates the wall model developed in OpenModelica, which receives solar radiation, outdoor air temperature and wall area as inputs, and provides the net heat flow rate as an output. For the windows, the model was extended as shown in Fig. 4 to include both conduction through glazing and radiative heat gain, calculated using the transmissivities of the glass panes. The model for the roof is similar to that of the wall, with a few additional algebraic blocks considered to compute the sol-air temperature using (5) instead of (4) (diagram for the roof not shown for the sake of brevity).

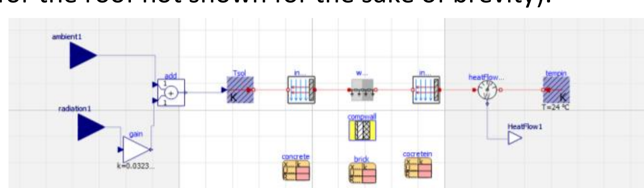


Fig. 3: Wall model

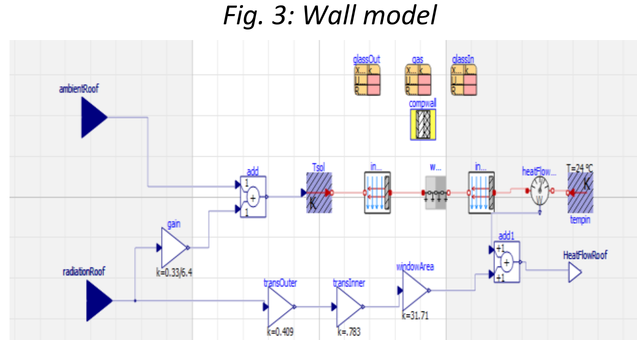
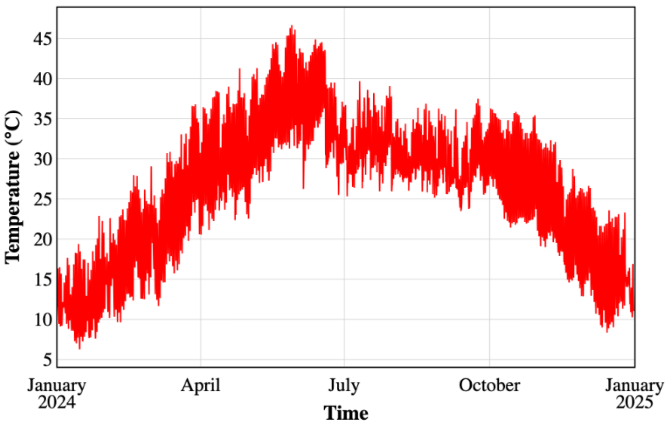


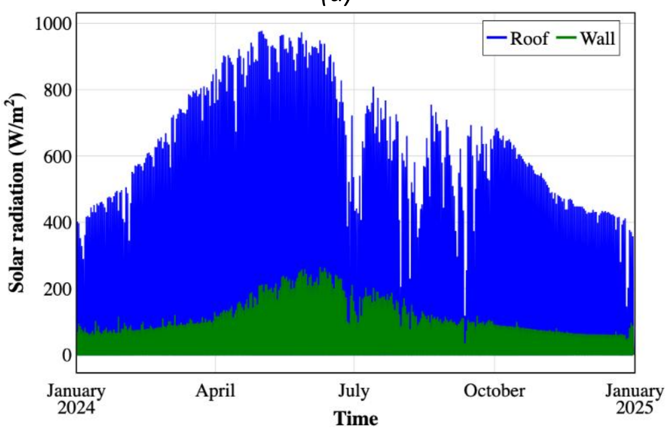
Fig. 4: Window model

2.4 Boundary Conditions

A weather monitoring station located outside the office premises was used to collect local data on ambient temperature. The temperature sensor of the device provided an accuracy of ±0.2 °C. Solar radiation data for the office space was obtained using IES VE. The collected information is shown in Fig. 5. Variations in ambient temperature and solar radiation were used as boundary conditions to determine the heat gain in the office space.



(a)



(b)

Fig. 5: Weather data used as boundary conditions: (a) ambient temperature; (b) solar radiation

3. MODEL VERIFICATION

To verify the credibility of the results obtained from simulations in OpenModelica, a verification exercise was performed to compare simulation outputs with experimental data obtained from [15]. In the reference, an experimental setup consisting of a cubicle with a periodic internal heat source was used to monitor the variation of heat flux and temperature on the surfaces.

The setup was placed inside a controlled temperature environment, so that the inner surfaces of the cubicle represented the outside surfaces of a building envelope, whereas the outer surfaces of the cubicle represented the inside surfaces of a building envelope.

A model of the experimental setup in [15] was developed in OpenModelica to represent a wall of the cubicle, with dimensions, material properties and boundary conditions borrowed from the reference. Results of the comparison are presented in Fig. 6. Upon simulation, a good agreement was observed between the model's outputs and the experimental data for heat flux, with a root mean square error of 0.67 W/m^2. These results provide confidence on the reliability of the model.

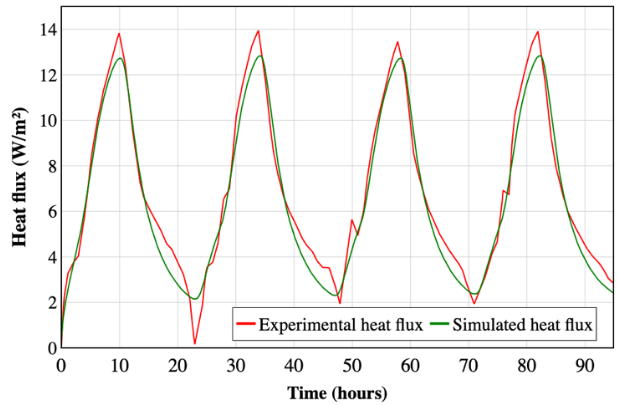


Fig. 6: Verification of the numerical model

4. RESULTS AND DISCUSSION

This section compares the thermal performance of a conventional brick wall with two retrofitted cases: one including a PCM layer and the other incorporating a PUF insulation layer. In all results, positive thermal demand denotes cooling demand, while negative values represent heating demand.

The results are presented in three subsections: the annual variation in thermal demand for 10 mm retrofits; detailed seasonal analyses for winter and summer conditions; and a parametric study assessing the effect of varying retrofit thickness in summer and winter.

4.1 Thermal performance for 10 mm retrofits

4.1.1 Annual variation

Fig. 7 shows results for the three building envelope configurations. The conventional brick wall (blue trace) exhibited the largest fluctuations in thermal demand due to its comparatively low thermal resistance. This allowed internal heat gains to dissipate more rapidly than through the insulated wall (red) or PCM-upgraded wall (green), which could reduce cooling demand in winter. However, during periods of high external temperatures, this resulted in a much higher cooling demand, with peak loads reaching approximately 4,700 W. These scenarios are discussed in detail in the following sections.

The PCM is designed primarily to reduce peak cooling load rather than to provide insulation. This resulted in peak fluctuations similar to the brick wall. In contrast, the

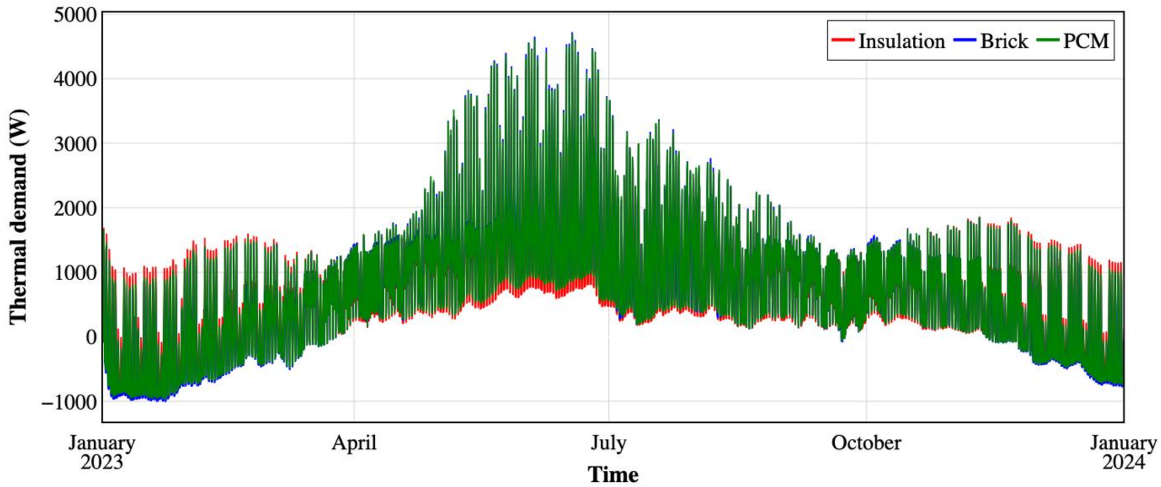


Fig. 7: Hourly thermal demand throughout the year

insulation layer consistently delivered the lowest average and peak cooling demand throughout the year, with a peak value of ~4,650 W.

4.1.2 Winter performance

To assess the impact of colder winter temperatures on the three configurations, three days within the winter months were selected. Results are shown in Fig. 8. The brick wall (blue trace) outperformed both the PCM wall (green) and the insulation (red) for peak cooling demand. This is due to the source of heat gains: as all the heat is produced internally, the lower thermal resistance expels excess heat to the external environment faster than the insulated wall (this effect could be mitigated by opening windows and doors). The PCM behaved as intended; however, in this scenario, it maintained the internal temperature, resulting in an additional 50 W of cooling demand during the day.

The insulated material retained more heat, which led to a peak cooling demand of ~1,500 W compared to 1,350 W for the PCM wall and 1,300 W for the brick wall. This behaviour is reversed if internal gains are removed, but due to lower external air temperatures, the room exhibits heating demand rather than cooling demand.

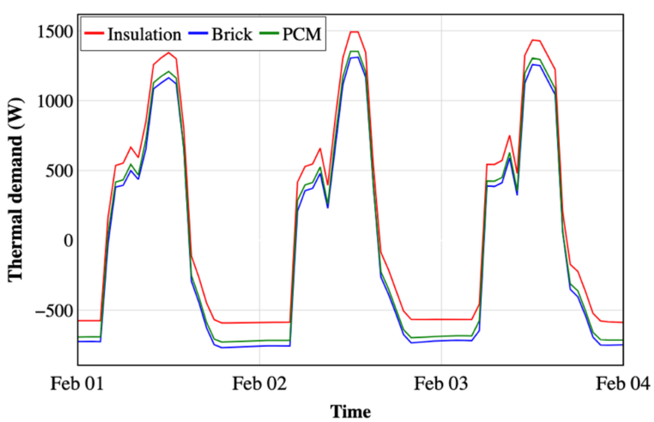


Fig. 8: Hourly thermal demand for winter

4.1.3 Summer performance

Three days were selected in the summer months with results shown in Fig. 9. The peak thermal demand occurred shortly after the scheduled lunch break. The brick wall (blue) exhibited a load of ~4,500 W, the PCM (green), which aimed to shave peak temperature only, reduced this load by ~50 W. The greatest load reduction was achieved with insulation, down to ~4,300 W.

Overall, these results indicate that in hot climates, insulation provides superior performance for peak cooling load reduction, yielding a 4.5% lower maximum thermal demand compared to conventional brick walls. This would lead to reduced energy consumption for active cooling systems and enhanced thermal comfort under extreme summer conditions.

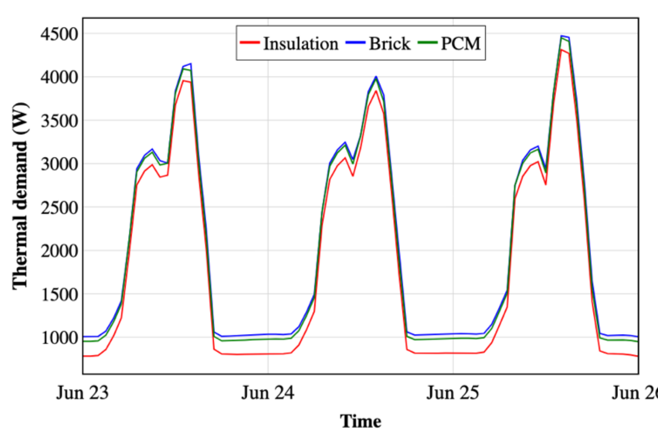


Fig. 9: Hourly thermal demand for summer

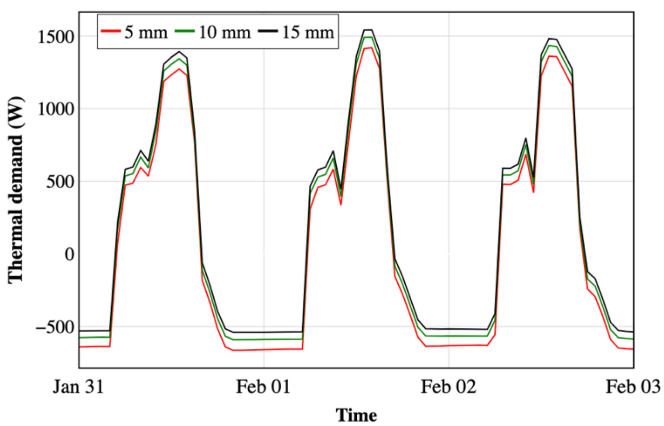
4.2 Parametric analysis of retrofit thickness

Adjusting the thickness of the PCM layer directly affects its thermal performance, as it changes the available volume to store heat. To investigate this, simulations for winter and summer were repeated for PCM thicknesses of 5 mm, 10 mm and 15 mm. The same approach was applied to the insulation layer.

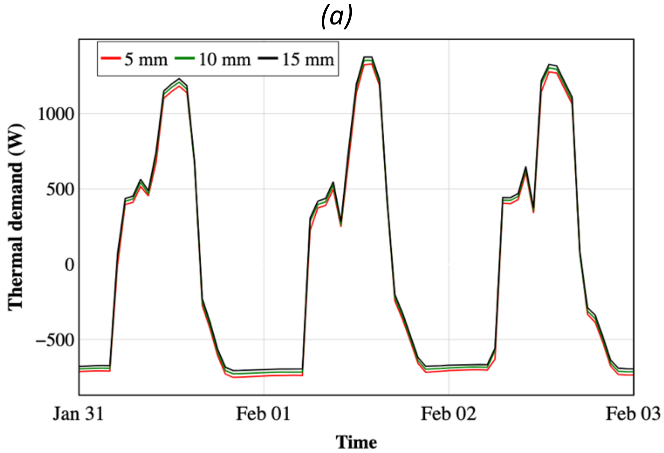
4.2.1 Winter performance

Three days were selected to assess winter performance, with results shown in Fig. 10. As shown in Fig. 10(a), increasing the thickness of the insulation negatively impacted cooling demand. This is seen with the 15 mm layer (black trace) having a peak cooling demand of 1,550 W compared to the 5 mm layer (red) exhibiting a peak demand of 1,400 W. As in Section 4.1.2, this behaviour was caused by the indoor temperature exceeding the outdoor temperature due to the internal gains. Higher thermal resistances caused by the thicker material retained heat in the room more effectively and thus increased cooling demand.

Similarly, Fig. 10(b) shows a comparable effect for PCM thickness, with peak cooling demand increasing from approximately 1,300 W for 5 mm to 1,400 W for 15 mm. This was caused due to the additional thermal storage capacity of the thicker PCM combatting the heat transfer through the wall. However, due to the minimal impact of the increasing thickness on the thermal resistance, outside of the peak temperatures, the cooling demand differences are smaller.



(a)

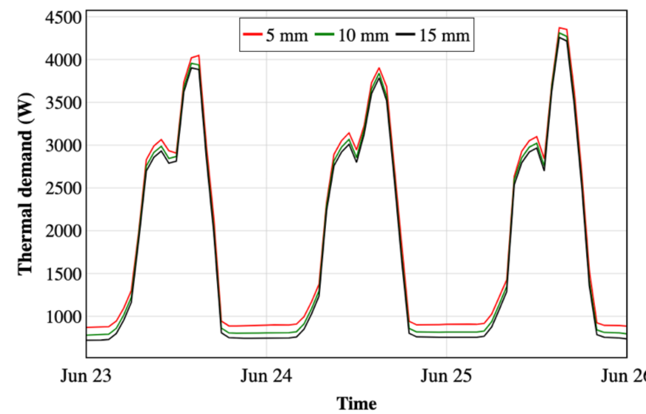


(b)

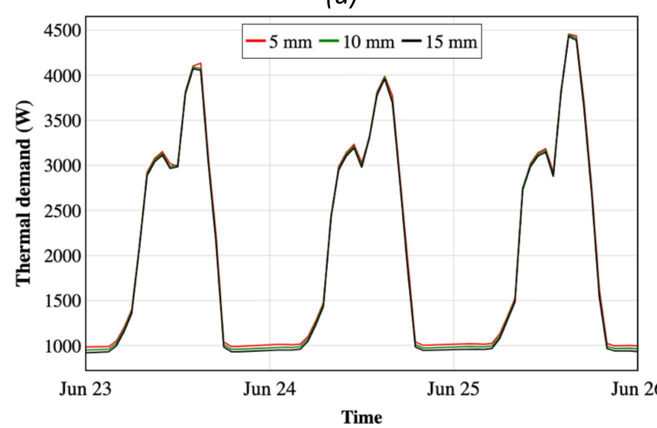
Fig. 10: Thermal demand variation for winter with different thickness of (a) insulation; (b) PCM

4.2.2 Summer performance

Three days were selected during summer, with simulation results presented in Fig. 11. As shown in Fig. 11(a), increasing the insulation thickness significantly reduced the peak cooling demand. The smallest insulation layer (5 mm, red trace) resulted in the highest peak cooling demand of 4,400 W, while the largest insulation layer (15 mm, black trace) reduced the peak to 4,250 W. PCM thickness had a less pronounced effect: the 5 mm PCM layer (red trace) reached a peak cooling load of 4,450 W, whereas the thickest PCM layer (15 mm, black trace) reduced it by ~50 W to 4,400 W.



(a)



(b)

Fig. 11: Thermal demand variation for summer with different thickness of (a) insulation; (b) PCM

4.3 Energy performance enhancement

Retrofitting the building envelope with adequate material reduces cooling demand in summer and increases cooling demand in winter for the office space considered. These effects have a direct impact on the electricity consumption by the heating, ventilation, and air conditioning (HVAC) system in place that maintains a constant indoor temperature.

To obtain an estimate of the savings or increase in electricity input to the HVAC system, a coefficient of performance of 3 was assumed [16]. With a 15 mm thick insulation layer, the peak electricity saving amounted to 83.3 W in summer. In contrast, the same thickness of insulation in winter caused an additional peak electricity consumption by a similar amount of 83.3 W.

In the tropical climate of India, hot summer spells are significantly longer than cold winter spells. Therefore, although the peak electricity saving in summer and additional peak electricity consumption in winter are similar, there will be a net electricity saving considering the longer summer period. It is therefore recommended to retrofit the office envelope with 15 mm insulation for an overall energy performance enhancement annually.

5. CONCLUSIONS

This paper presented an open-source Modelica-based model to assess the impact of envelope retrofit strategies on the thermal performance of an office space in the composite climate of Delhi, India. Real data for weather, building construction, occupancy schedules and internal loads were used to simulate different retrofitting scenarios including PCM integration and increased thermal insulation.

Results show that thermal insulation outperformed PCM-based and brick walls in mitigating annual thermal demand, reducing peak cooling loads by up to 4.5% compared to the reference case.

The thickness of retrofits is an important factor influencing thermal demand. With increasing thickness, the effectiveness of thermal insulation during summer at reducing thermal demand increased. In winter, the increased thermal resistance resulted in a higher cooling demand due to the indoor temperatures being higher than the outdoor temperature and the increased heat retention from the building. However, thickness variations in PCM in these seasons had marginal effects on its thermal demand moderation effects.

The presented results indicate that thermal insulation provides the most robust year-round reduction in cooling load for the office space under study and its climatic characteristics. In addition, the open-source model reported in the paper may enable practitioners to quantify retrofit impacts under different climatic conditions, supporting evidence-based decisions for sustainable cooling strategies.

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